

**Final Report for Period:** 10/2005 - 09/2006**Submitted on:** 12/21/2006**Principal Investigator:** Janata, Jiri .**Award ID:** 0327608**Organization:** GA Tech Res Corp - GIT**Title:**

SENSORS: SOLID STATE INTEGRATED PLATFORM FOR SENSING ARRAYS

**Project Participants****Senior Personnel****Name:** Janata, Jiri**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Zhou, Zhiping**Worked for more than 160 Hours:** Yes**Contribution to Project:**

On project until March 31 2005.

**Name:** Meindl, James**Worked for more than 160 Hours:** Yes**Contribution to Project:**

On project since April 1, 2005.

**Post-doc****Graduate Student****Name:** Chen, Hang**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Sasaki, Isao**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Rambhatia, Arun**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** L'Heerec, Frederic**Worked for more than 160 Hours:** Yes**Contribution to Project:****Undergraduate Student****Name:** Yu, George**Worked for more than 160 Hours:** Yes**Contribution to Project:****Technician, Programmer**

**Other Participant****Research Experience for Undergraduates****Organizational Partners**

TU Dresden, Germany

IMM Mainz, Germany

ETH Zurich, Switzerland

**Other Collaborators or Contacts**

Dr. Ari Glazer, School of Mechanical Engineering - MEMS Á-jet design

Dr. Karin-Potje Kamloth, Technical University Dresden, Germany (IMM Mainz, Germany) - Testing of organic semiconductor for organic electronics, on IDS and OFET/IGFET substrates fabricated at Georgia Tech

Dr. Muhanad S. Bakir, Microelectronics Research Center, Georgia Institute of Technology - Design of interconnects for GT05 array chip (3rd year)

Dr. Andreas Hierlemann, ETH Zurich, Switzerland

Dr. Mira Josowicz, Georgia Tech

**Activities and Findings****Research and Education Activities: (See PDF version submitted by PI at the end of the report)**

Attached.

**Findings: (See PDF version submitted by PI at the end of the report)**

Attached.

**Training and Development:**

Postdocs: Hang Chen

PhD Students: Hang Chen (2005), Isao Sasaki, Arun Rhambatia, George Yu

MSc Students: Frederic L'Heerec (2004)

Arun Rambathle (2006)

George Yu

**Outreach Activities:**

Jiri Janata chaired NRC, the sub-committee on Chemical and Biological Threat to US air Transportation. The report issued in 2006 (Publication 11).

Continuation of the maintenance of the popular NSF Workshop site:  
<http://www.chemistry.gatech.edu/sensingforum-02/welcome.html>

**Journal Publications**

Hang Chen, Mira Josowicz, Karin Potje-Kamloth and Jiri Janata, "Chemical Effects in Organic Electronics", Chem. Materials, p. 4728, vol. 16, (2004). Published

J. Janata, "Thirty Years of CHEMFETs", Electroanalysis, p. 18311835, vol. 16, (2004). Published

J. Janata, "Electrochemical microsensors", Proc. IEEE, p. 864, vol. 91, (2003). Published

J. Janata, M. Josowicz, "Conducting polymers in electronic chemical sensors", Nature Materials, p. 19, vol. 2(1), (2003). Published

Hang Chen, F. L'Hereec, I. Sasaki, J. Janata, "High-aspect ratio permanent photomask for solid-state chemical sensing array", Thin Solid Films, p. 241, vol. 444, (2003). Published

J. Janata, "Organic semiconductors in molecular electronics", Phys. Chem. Chem. Phys., p. 5155, vol. 5, (2003). Published

F. L'Hereec, Hang Chen, Zhipin Zhou, J. Janata, "New platform for testing organic field-effect transistors", J. Phys. Chem. B, p. 9042, vol. 108, (2004). Published

Isao Sasaki, Ari Glezer, Mira Josowicz, Jiri Janata, "Fast gas sensing using an integrated synthetic jet actuator", IEEE Sensors, p. 1728, vol. 6, (2006). Published

Hang Chen, Arun Rambathla, Karin Potje-Kamloth, Jiri Janata, "Study of electric field-modulation in organic field-effect transistors", J. Electrochem. Soc., p. , vol. , ( ). Accepted

Isao Sasaki, Mira Josowicz, Jiri Janata, Ari Glezer, "Enhanced performance of a filter-sensor system", The Analyst, p. 751, vol. 131, (2006). Published

#### **Books or Other One-time Publications**

J. Janata et. al., "Defending the US Air Transportation System Against Chemical and Biological Threats", (2006). Book, Published  
Bibliography: National Academies Press, ISBN 0-309-10074-7

J. Janata, "Principles of Chemical Sensors", ( ). Book, in preparation  
Bibliography: 2nd edition, Springer Verlag

#### **Web/Internet Site**

##### **URL(s):**

<http://www.chemistry.gatech.edu/sensingforum-02/welcome.html>

##### **Description:**

#### **Other Specific Products**

#### **Contributions**

##### **Contributions within Discipline:**

'Principles of Chemical Sensors', 2nd edition, Springer Verlag (expected publication date 2007)

##### **Contributions to Other Disciplines:**

Recruitment of all major engineering and scientific disciplines for rational improvement of security of civilian spaces and of public transportation.

**Contributions to Human Resource Development:**

The training of students, particularly undergraduate students, has been a major educational thrust of this project. We have signed up one new graduate and one undergraduate student.

**Contributions to Resources for Research and Education:**

Both the IGFET/OFET platform and the planar 4-point probe platform have been made available to other researchers throughout the world.

**Contributions Beyond Science and Engineering:**

**Categories for which nothing is reported:**

Any Product

Contributions: To Any Beyond Science and Engineering

## **Activities and Findings (Percentages of effort in parentheses)**

### **Chemical Electronics (25%)**

In “chemical electronics” traditional materials, e.g. silicon, silicon-related dielectrics and conventional metals are combined with non-traditional electronic materials, such as organic semiconductors and/or organic dielectrics in order to obtain a functionality beyond electrical signal processing. Solid-state chemical sensors and organic field-effect transistors belong to this category. In order to compare the performance of these two device types on the same scale a dual-purpose chip has been designed. It can be operated either as a conventional silicon IGFET or as an OFET. In order to fabricate it we had to develop a high aspect ratio photomask, that could be used to apply solvent-cast organic semiconducting films and to withstand thermal stresses that develop during e.g. wire bonding step.

Publications 1,2,3,5

### **Origins of Signal Modulation in OFETs (25%)**

It has been found that when the insulator/organic semiconductor (OS) interface and at the metal/OS contacts are exposed to the same electric field from the gate, approximately 50% of the drain current modulation originates from the modulation of the space charge that develops in the vicinity of the drain contact. This leads to experimental artifact when one tries to estimate the carrier mobility from the ordinary IGFET current-voltage equations. It has been shown that this is not a material problem, but a fundamental design issue originating from the co-planar geometry of the OFET. The major implication of this result is that the material properties of OS cannot be evaluated from the planar OFET structures without correction for the contact resistance.

Publications 4, 9

### **Monolithic CHEMFET/CMOS Array (30%)**

The ability to integrate solid state chemical sensors with monolithic supporting electronics has been a long-standing dream and promise of sensor developers. We have designed and fabricated an 8-channel CHEMFET array on the chip on which a monolithic CMOS support controlling and data processing circuitry has been built previously. This “post-processing” approach utilized the MiRC fabrication facility at the Georgia Tech, in which individual devices, such as CHEMFETs and the above test platforms have been successfully fabricated. The CMOS circuits supporting the array

consisted of approximately 150 transistors. At that level, the overall circuit yield was nearly zero. Although possible “in principle” the monolithic fabrication approach cannot work in practice due to incompatible fabrication standards for the chemical electronics and signal processing parts of the chip. This “hard learned” lesson serves as the take-off point for the practical solution outlined in the newly submitted NSF proposal.

#### **MEMS Gas-response Test Platform. (20%)**

In anticipation of the successful outcome of the fabrication of the CHEMFET/CMOS array a test-bed for evaluation of its performance has been built. It consisted of stereolithographically fabricated chamber for controlled, rapid delivery of gas samples . This test system can be used for *in situ* calibration of gas sensors and for testing performance and status of air filters . Although not originally planned as such, this application is important for homeland security deployment.

Publications 8,10

**Educational Activities:**

In the Spring semester 2006 both senior investigators were on partial sabbatical leave at the ETH Zürich and at the Weizmann Institute, respectively. The major objective was to write 2<sup>nd</sup> edition of the textbook “Principles of Chemical Sensors”. One student (Hang Chen) defended his PhD thesis and graduated in December 2005. Two students (F. L’Heerec and A. Rambathla) graduated with MSc in 2004 and 2005 respectively. We have trained one undergraduate intern.

Publication 12

### List of Publications

1. J. Janata, Proc. IEEE, 91, (2003) 864-869 "Electrochemical Microsensors"
2. J. Janata and M. Josowicz, Nature Materials, 2 (1), (2003) 19-24, "Conducting polymers in electronic chemical sensors"
3. Hang Chen, F. L'Hereec, I. Sasaki and J. Janata, Thin Solid Films, 444 (2003) 241-244, "High-Aspect Ratio Permanent Photomask for Solid-State Chemical Sensing Array"
4. J. Janata, Phys.Chem.Chem.Phys., 5 (2003) 5155-5158 "Organic Semiconductors in Molecular Electronics"
5. F. L'Hereec, Hang Chen, Zhipin Zhou and J. Janata, J.Phys.Chem.B. 108 (2004); 9042-9047 "New Platform for Testing Organic Field-Effect Transistors"
6. Hang Chen, Mira Josowicz, Karin Potje-Kamloth and Jiri Janata, Chem. Materials, 16 (2004) 4728-4735, "Chemical Effects in Organic Electronics"
7. J. Janata, Electroanalysis, (2004), 16, 1831-1835, "Thirty Years of CHEMFETs"
8. Isao Sasaki, Ari Glezer, Mira Josowicz and Jiri Janata, "Fast Gas Sensing Using an Integrated Synthetic Jet Actuator", IEEE Sensors, 6 (2006) 1728-1733
9. Hang Chen, Arun Rambathla, Karin Potje-Kamloth and Jiri Janata, "Study Of Electric Field-Modulation In Organic Field-Effect Transistors", J.Electrochem.Soc. (in print)
10. Isao Sasaki, Mira Josowicz and Jiri Janata and Ari Glezer, The Analyst, 131 (2006)751-756, "Enhanced Performance of a Filter-Sensor System"
11. J. Janata, et.al., Defending the US Air Transportation System Against Chemical and Biological Threats, National Academies Press, ISBN 0-309-10074-7, 2006
12. J. Janata, "Principles of Chemical Sensors", 2<sup>nd</sup> Edition, Springer Verlag, (in preparation)



## **Invited Lectures**

### **2004**

“Organic Electronics”, Abo Akademi, Turku, Finland, January  
“Nanomaterials for Chemical Sensing”, Nanochemistry Symposium, Finland, January  
“Chemical Plume Tracking”. Tufts University, Boston, April,  
“Chemical Effects in Organic Electronics”, NIST, Gaithersburg, April  
“Chemical Effects in Organic Electronics”, ECS Meeting, San Antonio, May  
“Au Nanoclusters in Polyaniline”, ECS Meeting, San Antonio, May  
“Why Not CHEMFETs”?, ACS Conference on Chemical Sensors, Santa Fe, May  
“Thirty Years of CHEMFET”, Honeywell, Minneapolis, August  
“Thirty Years of CHEMFET”, Hewlett-Packard, Corvallis, October  
“Chemical Effects in Organic Electronics”, U. of Oregon, Eugene, October

### **2005**

“Can Sensors Protect Enclosed Spaces?”, GRC, January, California  
“New Strategies For Analytical Chemistry in Homeland defense”, AAAS Meeting, February, Washington DC  
“Organic Semiconductors in Sensors and Electronics”, T. Shevchenko National University, Kiev, Ukraine, April  
“Chemical Modulation of Organic Semiconductors”, “Materials for 21<sup>st</sup> Century”, Edinburgh, UK, July  
“Organic Electronics Part I: Chemical Modulation”, Purdue Univ., July  
“Organic Electronics Part I: Electric Field Modulation”, Purdue Univ., July  
“Design Of Sensing Materials For Electrochemical Sensors”, ACCA, Kiev, Ukraine, September  
“Can Sensors Protect Public Places”, U. of Washington, Seattle, October  
“Origins of Modulation in Organic Field-Effect Transistors”, Inst. Mikrotechnik Mainz, Mainz, December

### **2006**

“Origins of Modulation of OFET”, Electrochemical Society Meeting, May, Denver  
“Modulation Effects in OFET”, Weizmann Institute, May, Rehovot  
“Modulation Effects in OFET”, U. TelAviv, June, TelAviv  
“Modulation Effects in OFET”, Hebrew University, Jerusalem, June  
“Can Analytical Chemistry Prevent Chem-Bio Terrorist Attack., SVU, June, C. Budejovice, Czech Republic  
“Modulation Effects in OFET” U. of Tennessee, October, Knoxville

### **Major Findings:**

- (A) Origins of signal modulation in Organic Field Effect Transistor have been identified. They are chemical (as in sensors) and physical. The resistance at the drain contact plays a major role in the latter. A new tool, modified four-point-probe platform has been designed for this study
- (B) In order to avoid that effect the contacts must be removed from the effect of the gate electric field. A non-planar IGFET/OFET platform was fabricated to accomplish this goal
- (C) A full scale integration of CMOS circuitry with chemical sensing arrays is difficult if not impossible to achieve in conventional fabrication facilities. A two-part fabrication strategy (i.e. separate chemical and electronic chips) utilizing high level interconnects is necessary.
- (D) Integrated platform for testing gas sensors/filters has been developed. It allows continuous monitoring of performance of gas sensors and air purification (i.e., HVAC) systems. It is significant for homeland security applications.